

# SPACE OPERATIONS ANALYSIS USING THE SYNERGISTIC ENGINEERING ENVIRONMENT

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## Abstract

The Synergistic Engineering Environment has been under development at the NASA Langley Research Center to aid in the understanding of the operations of spacecraft. This is accomplished through the integration of multiple data sets, analysis tools, spacecraft geometric models, and a visualization environment to create an interactive virtual simulation of the spacecraft. Initially designed to support the needs of the International Space Station, the SEE has broadened the scope to include spacecraft ranging from low-earth orbit to deep space missions. Analysis capabilities within the SEE include rigid body dynamics, kinematics, orbital mechanics, and payload operations. This provides the user the ability to perform real-time interactive engineering analyses in areas including flight attitudes and maneuvers, visiting vehicle docking scenarios, robotic operations, plume impingement, field of view obscuration, and alternative assembly configurations. The SEE has been used to aid in the understanding of several operational procedures related to the International Space Station. This paper will address the capabilities of the first build of the SEE, present several use cases of the SEE, and discuss the next build of the SEE.

## Introduction

With the increased need to reduce the time required to understand and solve engineering problems in fields of ever-increasing complexity, the National Aeronautics and Space Administration is continuing to develop the next generation of analysis and planning tools. One such tool, the Synergistic Engineering Environment (SEE) has been under development at the NASA Langley Research Center to aid engineers and scientists in their ability to more efficiently understand and analyze the design and operations of spacecraft. It has been designed to integrate analysis tools and their resultant data, with advanced visualization capabilities to provide a unique method for investigating various problem trade spaces. This can allow the entire multidisciplinary analysis team and management to have a clearer understanding of the key issues under investigation, minimizing lost time due to miscommunications, and focusing resources properly. Initially developed to support the analysis requirements of International Space Station, the SEE has more recently been expanded to support spacecraft operations ranging from low-earth orbit to deep space missions.

## Background

The SEE has been developed under several different programs within NASA. The SEE was initially started as a proof of concept project called the International Space Station (ISS) Immersive Accommodations Environment (IAE) [Angs00] under the funding of the Independent Program Assessments Office and the NASA Chief Engineer. The focus of the project at that time was threefold: fusion of disparate data, advanced human-computer interaction technologies, and distributed collaborative engineering. The ISS served as the prototype spacecraft within the software due to the engineering complexity of the ISS. The IAE was then adopted by the Intelligent Synthesis Environment (ISE) Program of NASA as one of the Large Scale Applications. These applications served as the focal point of

research for the development of a unified architecture and approach in the use of new technologies within NASA's engineering and scientific programs. At this time, the IAE was made available to the Vehicle Integrated Performance and Resources (VIPeR) Team at NASA Johnson Space Center (JSC) and renamed to the ISS Synergistic Engineering Environment. While under the funding of the ISE program, the focus of the ISS SEE software development remained in line with the initial goals. However, the major emphasis was placed on the requirements and usability issues resulting from the use of the software by the ISS VIPeR Team. With the cancellation of the ISE Program, most of the Large Scale Applications moved under the direction of the program in which they supported. Therefore, the SEE was moved under the direction of the ISS Program Office. Additionally, to offset the cost directly to the ISS Program Office, the Engineering for Complex Systems (ECS) Program has now provided funding and direction to the SEE project. Lastly, the capabilities of the SEE have been recognized and used for other spacecraft than the ISS within the Revolutionary Aerospace Systems Concepts (RASC) activity. Therefore, RASC funding and requirements have provided direction to the development of the current SEE capabilities. Under the current direction of the VIPeR Team, ECS, and RASC, the focus of the overall SEE development has broadened. However, the primary goals of the SEE still remain the same. This is the fusion of multidisciplinary analysis data and the corresponding analysis tools within an advanced visualization system to provide an interactive analysis tool such that the users shall gain additional insight into the broader dataset. Based on user requirements and feedback and limited resources, emphasis on research such as that on the use of voice recognition has been replaced with the cross platform development of the software.

### **Build One of the SEE**

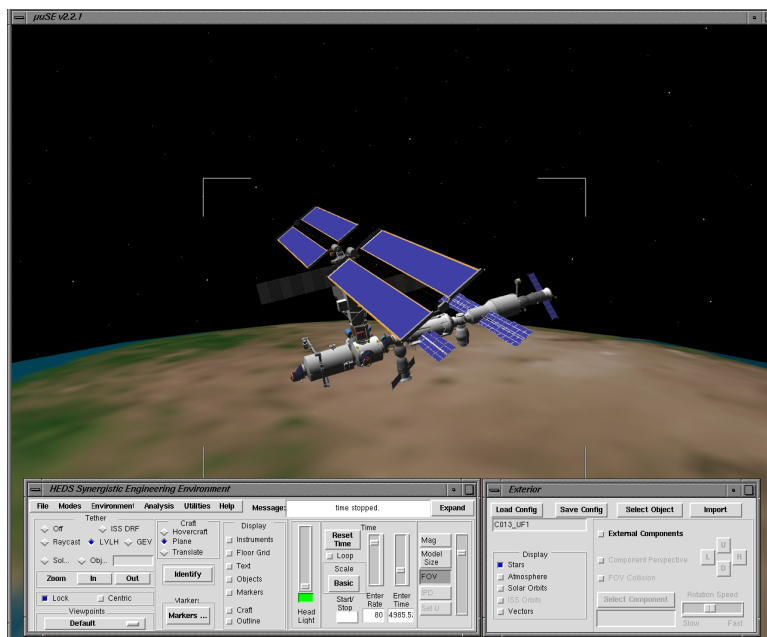
The first build of the SEE went through several iterations, such that each iteration added more analysis features and general capabilities. The initial version of the SEE was focused solely on the analysis of the ISS. By the end of development of the first build, a more general spacecraft operations analysis system had begun. Overall, the capabilities of the SEE can be broken down into three main categories: General Capabilities, Integrated External Analyses, and Internal Analyses.

#### *General Capabilities*

The SEE software consists of a virtual environment and a graphical user interface for interacting and controlling the simulations, as seen in Figure 1. The virtual environment includes a solar system simulation with all planets and moons modeled. Each planet and moon can be individually turned off or on to focus the simulation on the aspects of the solar system that are relevant for a given study. The solar system is mathematically propagated from an initial ephemeris data set to the date provided by the analysis. Within this solar system, the user can import spacecraft with trajectories and articular part motion. Since the primary responsibility of the first build of the SEE was to support the operations of the ISS, all the ISS assembly configurations are predefined and available in the environment. The user can also import new geometry models from a computer-aided design system or modeling system into the environment. Once in the SEE environment, the user can modify the models position, orientation, and mass property data to create new variations of the spacecraft.

Several different methods have been developed to enable the user to navigate throughout the environment. The first method is the ability to "fly" through the solar system utilizing a simple mouse driven navigation paradigm. In this manner the user can freely move through the environment to any location. However, since the solar system is a vast space, it is very difficult to locate an object. Therefore, the use a tethering mechanism is the primary method of navigation. The user can select any object within the scene through the use of the graphical interface and the software will move the user to that object and initiate a tether between the user and the object. Once initiated, the user will automatically move relative to the motion of the object. Within tethered navigation, the user still has the ability to move

around the object while maintaining a fixed direction of gaze towards the object, thus allowing the user to view the object from different perspectives.



**Figure 1. SEE Graphical Environment and Interface**

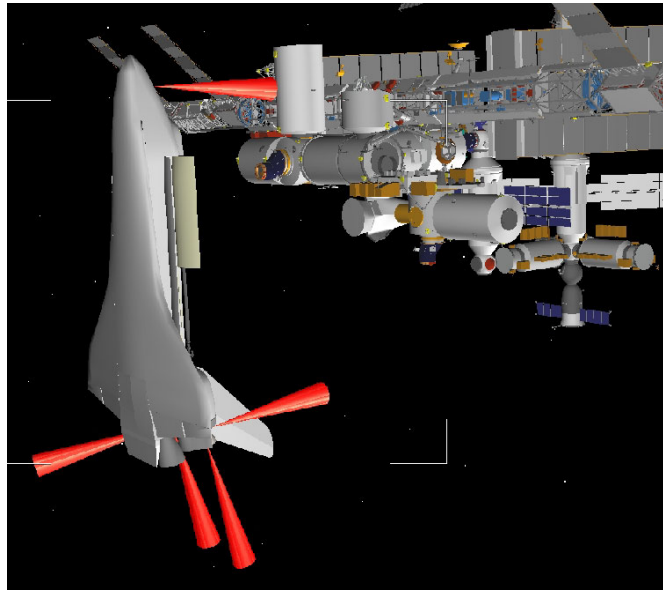
Since the SEE is a time-dependent simulation, several different time controls have been designed for the environment. The application has a start time and end time associated with each simulation. The user can start, stop and reset time at any time within the simulation. The speed of the data playback, both forwards and backwards, can also be controlled. If a particular time contains data of interest, the user can save that position through a time marker to return to that time at a later date.

### *Integrated External Analysis Capabilities*

Once the user has setup the environment with the appropriate solar system configuration and spacecraft, there are several different analysis capabilities that can be utilized. The primary capability is the use of rigid body dynamics to analyze the motion of the spacecraft as it orbits. Two different analysis systems have been integrated into the first build of the SEE. The first system, called Attitude Prediction (ATTPRED) [Henr91], calculates the spacecraft's attitude and rigid body articulation over a circular earth orbit based on the subjected environmental and controls forces and torques. This software was written at NASA Langley Research Center and has been utilized for the analysis of the ISS. Inputs to this system include mass and inertia properties, frontal area properties, articulating part data, control strategies and environmental parameters such as atmospheric and gravitational properties. An interface was developed that links the relevant data from the SEE software to the ATTPRED software. Once the analysis has been run, the data is automatically sent to the SEE software for review and playback. The second system, called Space Station Multi Rigid Body Simulator (SSMRBS) [Aero00], also calculates the attitude and rigid body articulation but specifically for the ISS. SSMRBS has been written at NASA Johnson Space Center and is the baseline software for ISS analysis. This software contains a much more detailed input set based on the actual control systems algorithms of the ISS. As with ATTPRED, an interface was written to link the SEE software with SSMRBS to transfer data to between the two systems.

A docking simulation tool, called DockSim [Kuma96, Toni00], has also been integrated into the SEE as an additional external analysis capability. DockSim, written at NASA Langley Research Center, is a

generic optimal controls analysis system for analyzing vehicle docking trajectories. For any given ISS configuration, the SEE software automatically detects the presence of baseline docking vehicles such as, Shuttle, Progress, Soyuz. The user can also import a new vehicle into the SEE to be analyzed as a docking vehicle. Once a vehicle has been selected for analysis, the user can run the DockSim software and setup the operating conditions. Input parameters include docking vehicle starting position, orientation and velocity, ending position, orientation and velocity, mass and inertia properties, thruster setup, and docking corridor. The user also specifies an optimal control strategy as either minimal control effort or minimal time for docking. Docksim calculates a point mass trajectory and once solved, calculates the required jet firing sequence to fly that trajectory and the resultant spacecraft attitude. This data is then provided to the SEE software for visualization. A snapshot of an ISS/Orbiter docking scenario with thruster firings is shown in Figure 2.

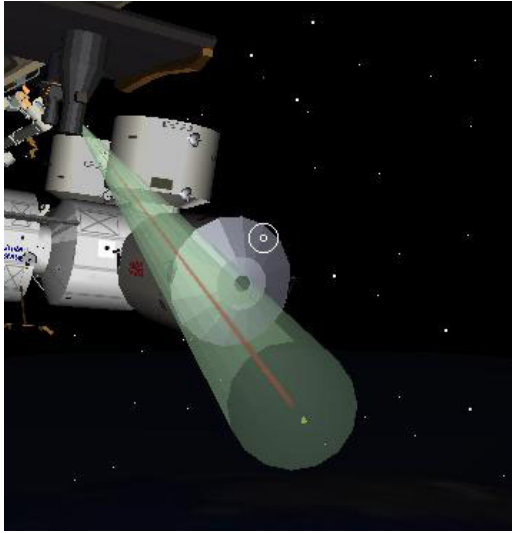


**Figure 2. Docking Analysis**

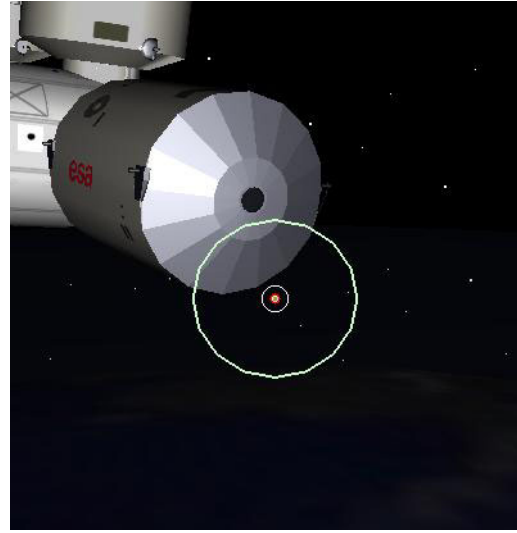
#### *Internal Analysis Capabilities*

In addition to the external analysis capabilities, several internal capabilities have been developed to support the operations analysis of the ISS and other spacecraft. The first capability introduced into the SEE was the use of field of view (FOV) cones. In general, FOV cones represent the view from a particular point in space towards another point. FOV cones were customized to handle analyses in areas such as communications, payload instruments, thrusters, and cameras. The user can specify the location and orientation of the FOV cone, specify the FOV angle and length of cone, control the FOV gaze direction during the simulation, and gain the perspective through the cone. Figure 3 and Figure 4 provide examples of the FOV cones for use with instrument viewing analysis. The use of FOV cones as thrusters can be seen in Figure 2.

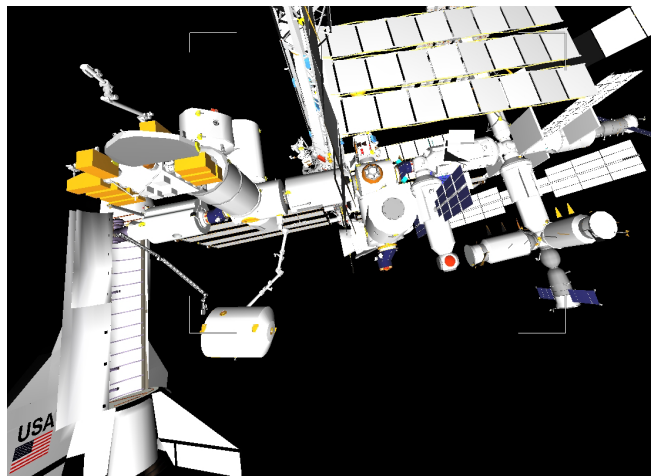
Another internal analysis capability is the robotics capability. The SEE software is capable of analyzing the robotic motions of the Space Station Remote Manipulator System (SSRMS) and the Shuttle Remote Manipulator System (SRMS). The user can interactively control either arm, subject to the constraints of the arm, such as angle limitations of each joint. Objects within the scene can be grappled, moved and released for the first order analysis of payload installation operations. Additionally, scripts can be loaded or saved based on the scripting language used by the Manipulator Analysis Graphics and Interactive Kinematics (MAGIK) Team at NASA Johnson Space Center. A sample analysis of a payload hand-off from the SSRMS to the SRMS is shown in Figure 5.



**Figure 3. SAGE III Instrument FOV**



**Figure 4. View from the SAGE III Instrument**



**Figure 5. SSRMS and SRMS Operations Analysis**

### **Use Cases of the SEE**

Since the creation of the first build of the SEE, it has been used in the analysis of several operational scenarios of the ISS. These include the operations of the Stratospheric Aerosol and Gas Experiment III, the contingency operations planning of the ISS in case of a Plasma Contactor Failure, and the operations playback of the ISS telemetry data.

### *SAGE III Payload Analysis*

The first use of the SEE was in support of the Stratospheric Aerosol and Gas Experiment III (SAGE III). The SAGE III instrument is an external payload that measures the content of the Earth's atmosphere utilizing the Sun and the Moon as a light source as it scans the atmosphere. This experiment is scheduled to be placed aboard the ISS in 2004 on an Express Pallet. To analyze the operations of the SAGE III, items such as the dynamic nature of the ISS motion, the articular part motion, the changing assembly sequence, the behavior model of SAGE III, and the orbit of the Earth must be taken into account. The SEE provided a platform for the analysis of the SAGE III data taking opportunities by fusing analysis

results into one environment. Previously, this analysis was performed using static models of the ISS within a CAD environment. Only a small selected set of cases could be analyzed in a reasonable amount of time. With the use of the SEE, an entire year's worth of operational conditions could be analyzed.

Although much of the needed capabilities were present in the SEE to model the behavior of the operations of the SAGE III instrument, a customized SAGE III analysis version was created to output the necessary data that the SAGE III team required. The result of this customization provided the SAGE III team the ability to setup an analysis of arbitrary operations length, with any ISS configuration, starting at anytime in the future. The SEE would output for each day of the year, the instruments operational results for that day. These included time operational, the orientation of the instruments lens, any blockage of the field of view of the instrument, any blockage of a larger "safe zone" to protect against glinting, and what ISS objects were responsible for the blockage. Shown in Figure 3 is a snapshot of the SEE software of the SAGE III instrument and its field of view cones viewing a high beta angle condition near the Columbus module. Figure 4 shows the view from the SAGE III instrument.

Several different scenarios were run to support the SAGE III team. A typical simulation covered one year of operations with assumptions such as using the UF-4 configuration of the ISS, an altitude profile that would take into account orbit decay and reboost, and a TEA of 5.0 yaw, 6.6 pitch, 0.5 roll. Additionally the SAGE III operations behaviors were modeled. These included the atmospheric altitude ranges for data taking opportunities, sun beta angle constraints, yaw and pitch constraints of the hexapod mount, and pitch constraints of the instrument's mirror. A sample of the data produced from the SEE is shown in Figure 6. This plot shows the total possible amount of time the SAGE III instrument could collect data given no operational constraints. Overlaid on this is the time available taking into account yaw limitations of the instrument due to thermal constraints. Finally, the last overlay shows the amount of time available for data collection taking into account blockage due to ISS components.

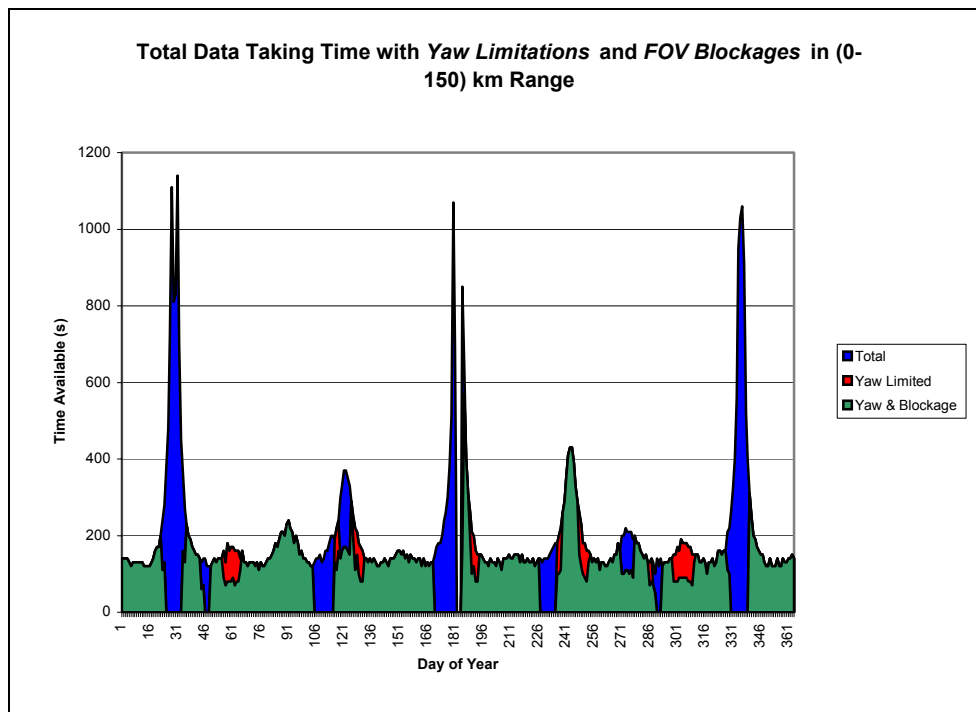


Figure 6. Sample Output for SAGE III Analysis

In addition to the one year operations simulation of the SAGE III instrument, several other investigations were performed using the SEE. These include alternate ISS configuration impacts on the operations of SAGE III and contingency placement positions of the SAGE III instrument in the event that the Express Pallet was not available. These analyses were performed through general visualization of the operations in real-time and were not quantitative in nature.

#### *PCU Failure Contingency Study*

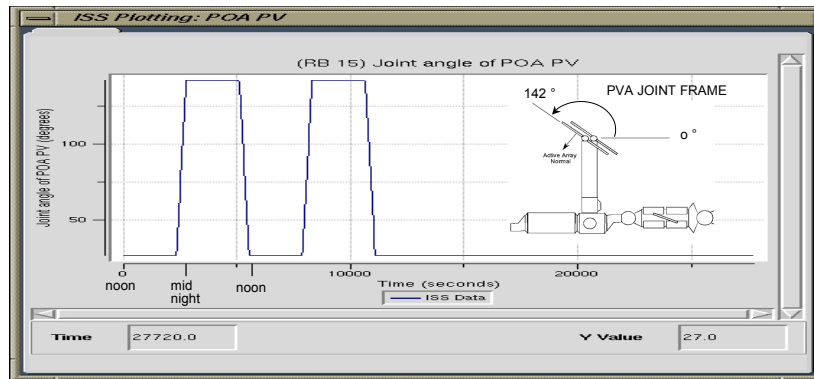
One of the SEE strengths is the visualization of the overall flight characteristics of a spacecraft. The Vehicle Integrated Performance and Resources (VIPeR) Team at NASA Johnson Space Center (JSC) utilized the SEE to better understand and communicate the necessary flight changes needed to be performed in the event of a complete plasma contactor unit (PCU) failure. The PCUs control the electrical buildup on the exterior of the ISS due to plasma. When the active sides of the solar arrays are pointed into the ram direction, the electrical potential buildup on the ISS increases. In the event of a PCU failure, an extravehicular activity or EVA would need to be performed for repair of the unit. This could pose a threat to the astronaut due to the potential for a large electrical buildup. Therefore, ISS operations would need to change the attitude of the vehicle and the motions of the solar arrays to minimize this buildup while maintaining maximum power generation to minimize the effect on the overall ISS requirements. For the nominal XVV flight mode, these changes were fairly readily understandable by the various domain experts. However, during XPOP flight control, these constraints are very difficult to understand and visualize.

Upon development of these proposed changes to the ISS flight operations, the SEE was used to visualize and communicate these changes to upper management and discipline experts. Figure 7 shows an image taken from the SEE with the ISS orbiting in XPOP flight mode with the solar arrays in one of the several necessary locked positions. The arrow pointing to the bottom right is the velocity vector. The arrow pointing to the upper left is the sun direction. The last arrow points in the direction of the spacecraft's X axis. It can be seen that the arrays are not perpendicular to the Sun vector since they are locked and not tracking the Sun. During this portion of the orbit, the locked position will cause a loss in power generation capabilities, but minimize electrical buildup. Figure 8 is a plot showing the motion of the arrays over one orbit of flight. The fact that these pictures do not convey all the required information to the reader to clearly understand these motions due to the time-based nature of the data shows the necessity for a virtual simulation to assist in overall better understanding of the contingency operations.



**Figure 7. PCU Failure Analysis for XPOP Flight**

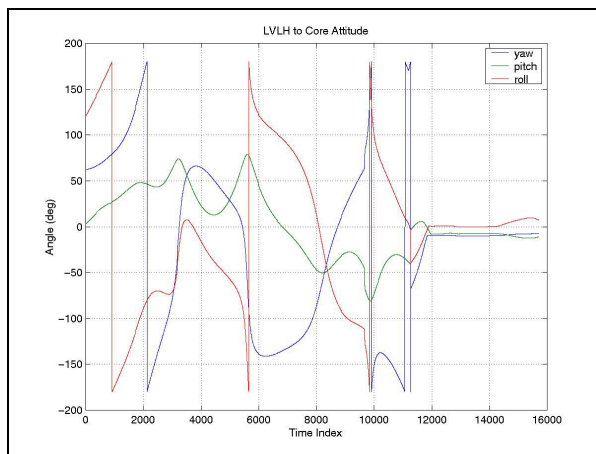




**Figure 8. Array Joint Angle Plot for PCU Failure Analysis**

### *Telemetry Playback*

As previously mentioned, the SEE is very effective at visually communicating the overall flight dynamics of a spacecraft. For this reason, the VIPeR Team at JSC has utilized the SEE to playback actual telemetry data for several instances of long periods of free flight of the ISS. The plot shown in Figure 9 is the YPR Euler angle sequence of the motion of the ISS over several orbits. It is very difficult to decipher the overall motion based on these plots. However, using the SEE, the engineers and managers were able to easily see the motions of the ISS. A snapshot in time of the telemetry playback within the SEE is shown in Figure 10. The vector pointing to the left indicates the velocity vector. Initial planning has begun on establishing a secure link within JSC to enable the VIPER Team to use the SEE to visualize ISS real-time telemetry.



**Figure 9. Telemetry Data for ISS**



**Figure 10. Telemetry Playback in SEE**

### **Build Two of the SEE**

With the change in focus of the SEE from ISS-based to general spacecraft, the software architecture used for Build One was not easily extensible to handle the new requirements. Therefore, a new architecture was developed and is currently being implemented. In the design of Build Two of the SEE, there were several main areas in which changes were introduced to the overall software system. These changes were based on user feedback and new customer requirements. Areas of change include the user interface features, accessibility and deployability, and new analysis requirements. In addition to the introduction of

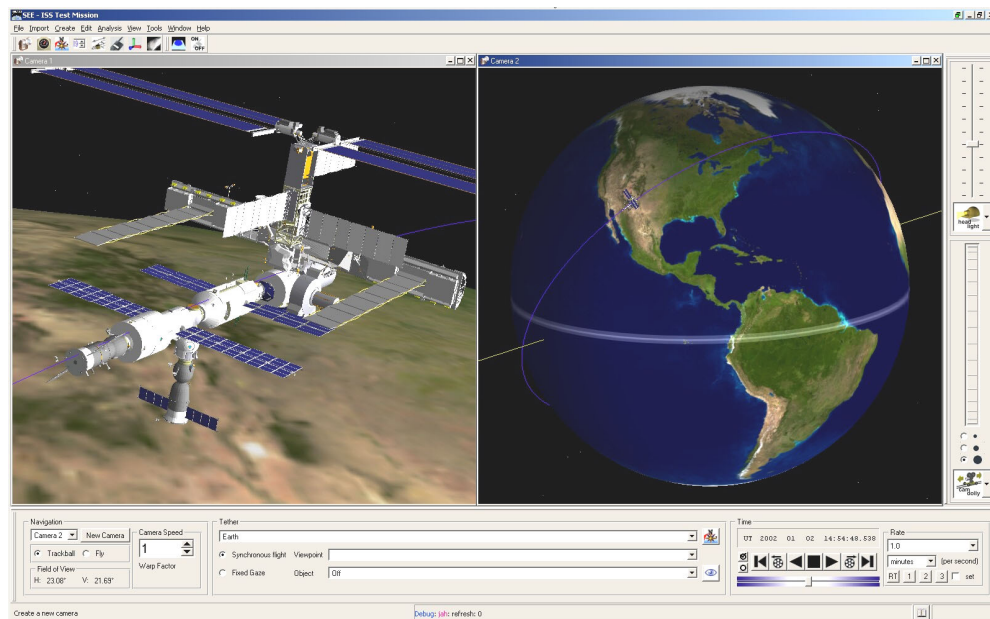


these new features, the features of Build One are also being re-implemented within the new architecture design. The order in which the features are being added is determined by customer requirements and available resources.

### *User Interface Enhancements*

Based on user feedback, the Build One user interface did not provide easy navigation within the scene and constrained the motion of the user with respect to obtaining a particular view. To address these concerns, Build Two of the SEE introduced a new navigation scheme, based on the keyboard and mouse. Although the Build One navigation utilized the mouse to move the user through the scene, the navigation methodology was dictated by the underlying graphics API. This methodology was not applicable within the domain of space operations and the scale of the solar system navigation. In Build Two, the navigation was written specifically to meet the needs of space navigation within the SEE. Therefore the user can easily navigate to any position, and obtain any orientation. This methodology is consistent in both the free flying mode of navigation and to the tethered mode of navigation. Additionally, the user can obtain multiple views into the scene for Build Two using multiple windows. Each window can be independently navigated, but are linked with respect to time. This can be seen in Figure 11. The left window shows a close up of the ISS and the right window shows an overview of the orbit with a scaled ISS on the orbit.

User control of time is another area in which significant emphasis was placed for Build Two. In Build One, there was little feedback provided to the user with respect to time. Build Two provides a full suite of tools available to the user with respect to time. The current time within the simulation is always displayed to the user. The user has direct control over the rate of playback for the simulation by setting the simulation rate relative to one second of real time. For instance, the user can specify a playback speed of 1 minute per second or 10 hours per second. The user can also save various rates for future use, as well as save a particular time into a time marker to return to later.



**Figure 11. ISS in SEE Build Two**

### *Accessibility/Deployability*

In the First Build of the SEE, the software was developed to run on Silicon Graphics high-end workstations, such as the Infinite Reality systems. These workstations are primarily set up in dedicated laboratories. For new users of the SEE, if a laboratory suitable for running the SEE was not available, a

considerable cost was required to set one up. Additionally, the users of the SEE were required to leave their office to go to the laboratory, which was not convenient. Although this does not seem like a problem, the need to take reference materials or schedule the use of the laboratory was often an annoyance. This was seen as a hindrance in the process of gaining a broad user base of the SEE. With the advances in computer hardware, it was deemed both feasible and a requirement to support desktop and portable platforms within the next build. Build Two is currently being developed and used across three platforms: Irix, Linux, and Win32. This allows the SEE to run in the dedicated laboratories on the high-end workstations, to be directly on a user's desktop system, or to be placed onto a laptop to take to a meeting.

### *Analysis Requirements*

There have been several changes to the SEE to support the analysis requirements of the various end users of the SEE. Build One of the SEE was developed to support analysis of one spacecraft in a given scene and required that all motions (i.e., orbit trajectories or articulated part rotations) of the spacecraft be calculated through the use of the integrated analysis programs. These limitations prevented the user from evaluating scenarios that were operationally possible, but not yet analytically modeled by any of the integrated analysis software. Therefore, in the development of Build Two, these cases were treated as use cases for the design of the new architecture. In Build Two, multiple spacecraft can be loaded and analyzed simultaneously within the SEE. This provides the capability to analyze multiple spacecraft within the same scene and their interdependencies. Additionally, for a given analysis, the motion of a spacecraft may be known or the user wants to dictate it to determine the effects on another system within the scene, such as communication relays or instrumentation line of site. The exact dynamics and control systems to make the spacecraft behave in such a manner may be difficult or impossible to model within the analysis software. In order to support these types of scenario developments, Build Two will allow the motion of each spacecraft and its associated joints to be scripted rather than only provided through an analysis package.

### **Conclusion**

The Synergistic Engineering Environment has provided engineers and scientists the ability to visualize, analyze, and communicate data associated with the various aspects of space operations. The fusion of data from different disciplines into one visualization environment allows teams to understand the cross dependencies of multidisciplinary data. By integrating the analysis tools into the environment, the SEE provides an interactive environment where multiple changes can be performed and the results can be analyzed immediately. This can provide a quick assessment of an operational concepts and procedures. Problems associated with an operation can be identified and the proper resources can be allocated to investigate a particular scenario in more detail.

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